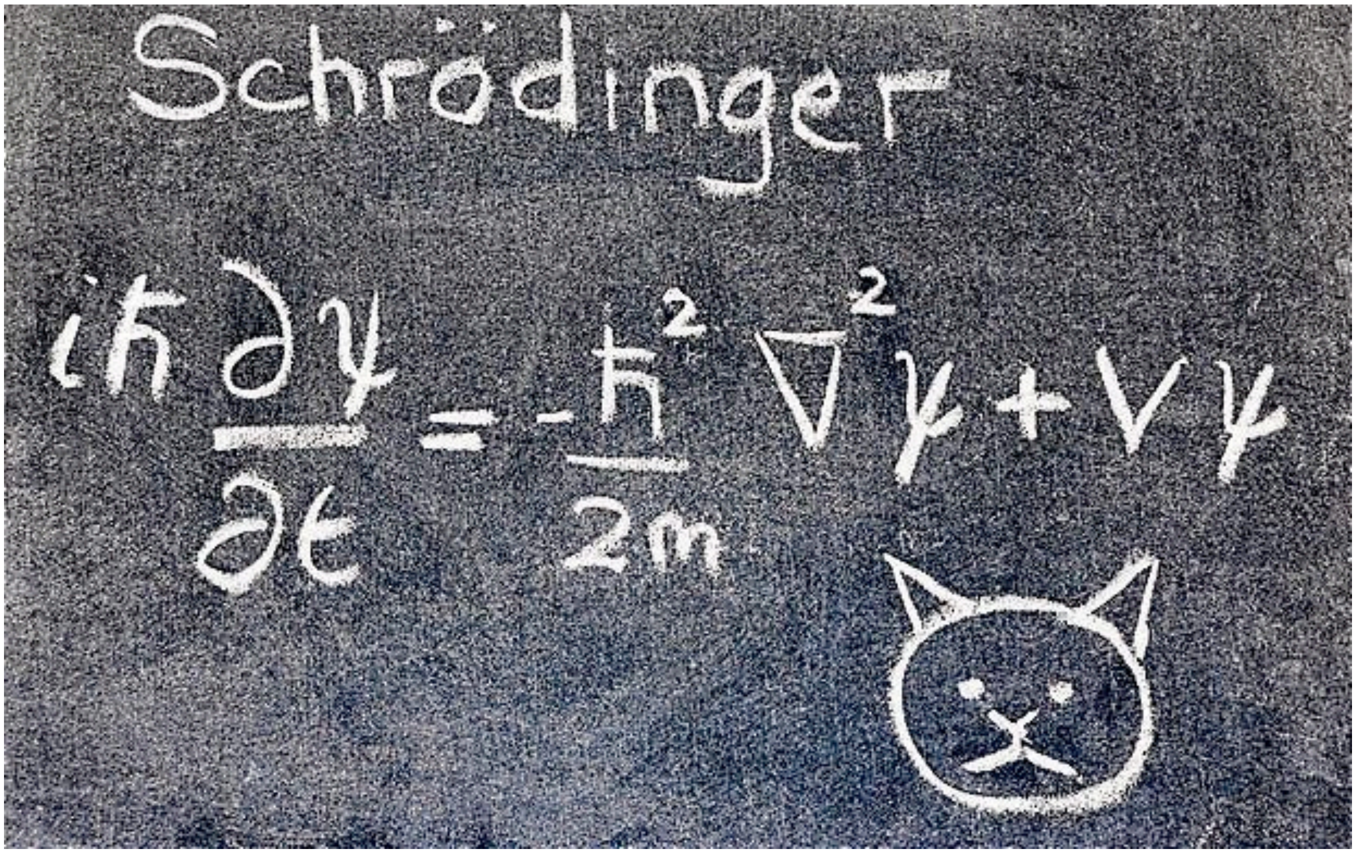
Models of Spontaneous Wave Function Collapse: an Update

115th Statistical Mechanics Conference

Rutgers University, 8 - 10 May 2016

(Angelo Bassi – University of Trieste & INFN)

Quantum Mechanics



Linearity ➔ Superposition Principle ➔ Schrödinger's cat ➔ Measurement Problem

Modify the Schrödinger equation

J.S.Bell
Speakable and Unspeakable in Quantum Mechanics

E.P. Wigner
in: Quantum Optics, Experimental gravity and Measurement theory, Plenum, NY (1983)

A.J. Leggett
Supplement Progr. Theor. Phys. 69, 80 (1980)

H.P. Stapp
In: Quantum Implications: Essay in Honor of David Bohm, Routledge & Kegan Paul, London (1987)

S. Weinberg
Phys. Rev. Lett. 62, 486 (1989).

R. Penrose
In: Quantum Concepts of Space and Time, Oxford U.P. (1985)

S.L. Adler
Quantum Theory as an emergent phenomenon CUP (2009)

G.C. Ghirardi, A. Rimini, T. Weber
G.C. Ghirardi, A. Rimini, T. Weber , *Phys. Rev. D* 34, 470 (1986)

P. Pearle
Phys. Rev. A 39, 2277 (1989)

L. Diosi
L. Diosi, *Phys. Rev. A* 40, 1165 (1989)

How to modify the Schrödinger equation?

The **no-faster-than-light condition** heavily constraints the possible ways to modify the Schrödinger equation.

In particular, it requires that **nonlinear terms** must always be accompanied by appropriate **stochastic terms**

N. Gisin, *Hel. Phys. Acta* 62, 363 (1989). *Phys. Lett. A* 143, 1 (1990)

N. Gisin and M. Rigo, *Journ. Phys. A* 28, 7375 (1995)

J. Polcinski, *Phys. Rev. Lett*. 66, 397 (1991)

H.M. Wiseman and L. Diosi, *Chem. Phys.* 268, 91 (2001)

S.L. Adler, "Quantum Theory as an Emergent Phenomenon", C.U.P. (2004)

A. Bassi, D. Dürr and G. Hinrichs, *Phys. Rev. Lett.* 111, 210401 (2013).

L. Diosi, *Phys. Rev. Lett.* 112, 108901 (2014)

M. Caiaffa, A. Smirne and A. Bassi, in preparation

The dynamics (simplified)

$$d|\psi\rangle_t \;=\; \Big[\underbrace{-\frac{i}{\hbar}H\,dt}_{\text{quantum}} \;+\; \underbrace{\sqrt{\lambda}(A-\langle A\rangle_t)\,dW_t - \frac{\lambda}{2}(A-\langle A\rangle_t)^2\,dt}_{\text{collapse}}\Big]\,|\psi\rangle_t$$

$$\langle A\rangle_t \;=\; \langle\psi_t|A|\psi_t\rangle \;\longrightarrow\; \text{nonlinear}$$

The wave function is dynamically and stochastically driven by the noise W_t towards one of the eigenstates of the operator A

This can be seen as a phenomenological equation, eventually to be derived from an underlying theory

(S.L. Adler's book on "Trace Dynamics")

(Mass-proportional) CSL model

P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

$$\frac{d}{dt}|\psi_t\rangle = \Big[-\frac{i}{\hbar} H + \frac{\sqrt{\gamma}}{m_0} \int d^3x \, (M(\mathbf{x}) - \langle M(\mathbf{x}) \rangle_t) \, dW_t(\mathbf{x}) - \frac{\gamma}{2m_0^2} \int \int d^3x d^3y \, G(\mathbf{x} - \mathbf{y}) \, (M(\mathbf{x}) - \langle M(\mathbf{x}) \rangle_t) \, (M(\mathbf{y}) - \langle M(\mathbf{y}) \rangle_t) \Big] |\psi_t\rangle$$

$$M(\mathbf{x}) = m a^\dagger(\mathbf{x}) a(\mathbf{x}) \qquad G(\mathbf{x}) = \frac{1}{(4\pi r_C)^{3/2}} \, \exp[-(\mathbf{x})^2 / 4 r_C^2]$$

$$w_t(\mathbf{x}) \equiv \frac{d}{dt} W_t(\mathbf{x}) = \text{noise} \quad \mathbb{E}[w_t(\mathbf{x})] = 0 \quad \mathbb{E}[w_t(\mathbf{x}) w_s(\mathbf{y})] = \delta(t - s) G(\mathbf{x} - \mathbf{y})$$

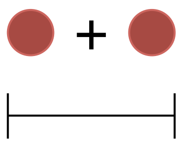
Two parameters

$$\gamma = \text{collapse strength} \qquad r_C = \text{localization resolution}$$

$$\lambda = \gamma / (4\pi r_C^2)^{3/2} = \text{collapse rate}$$

The collapse rate

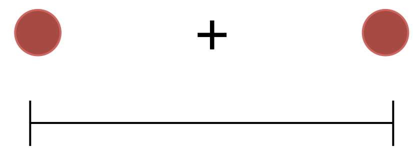
Small superpositions



$\ll r_C$

Collapse NOT effective

Large superpositions

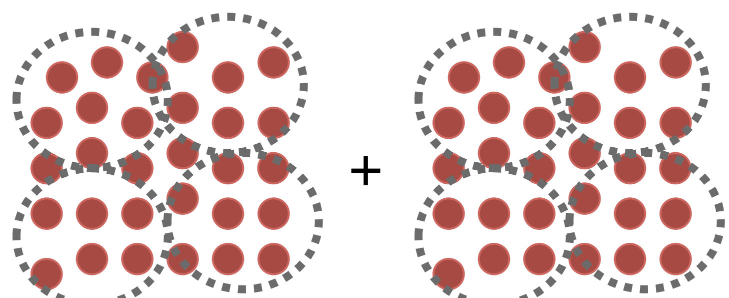


$\geq r_C$

Collapse effective

↓

$$\Gamma = \lambda n^2 N$$



n = number of particles within r_C

N = number of such clusters

Amplification mechanics

Few particles

no collapse

quantum behavior

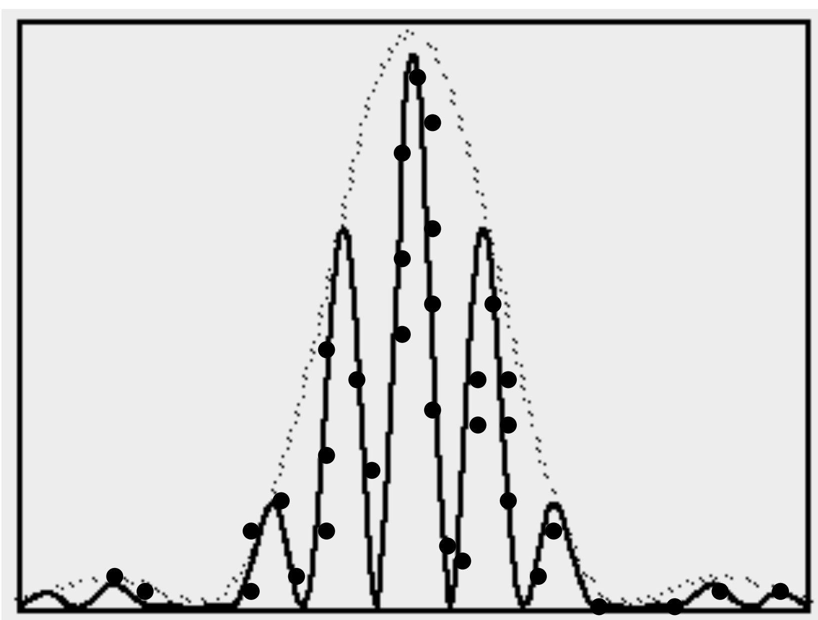
Many particles

Fast collapse

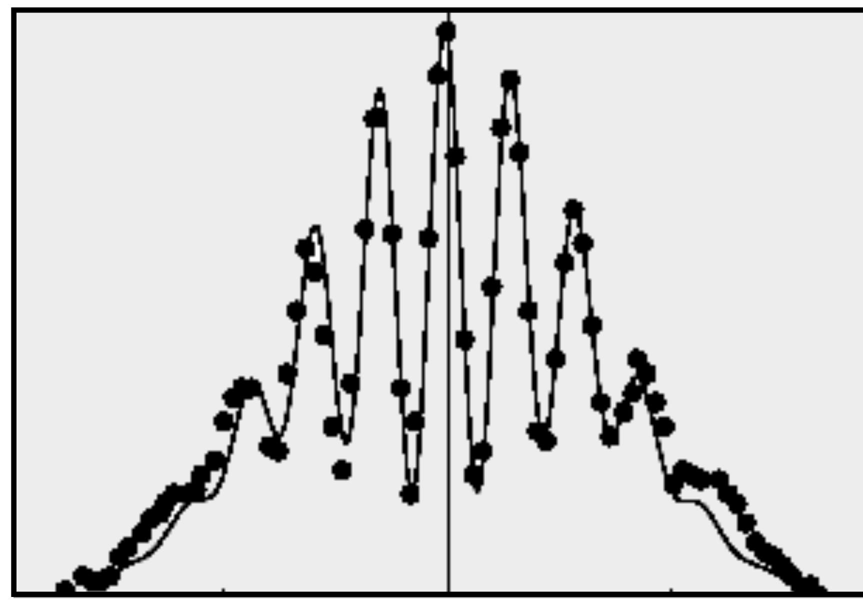
classical behavior

Experimental tests

The obvious way to test collapse models is with matter-wave interferometry



Prediction of quantum mechanics
(no environmental noise)



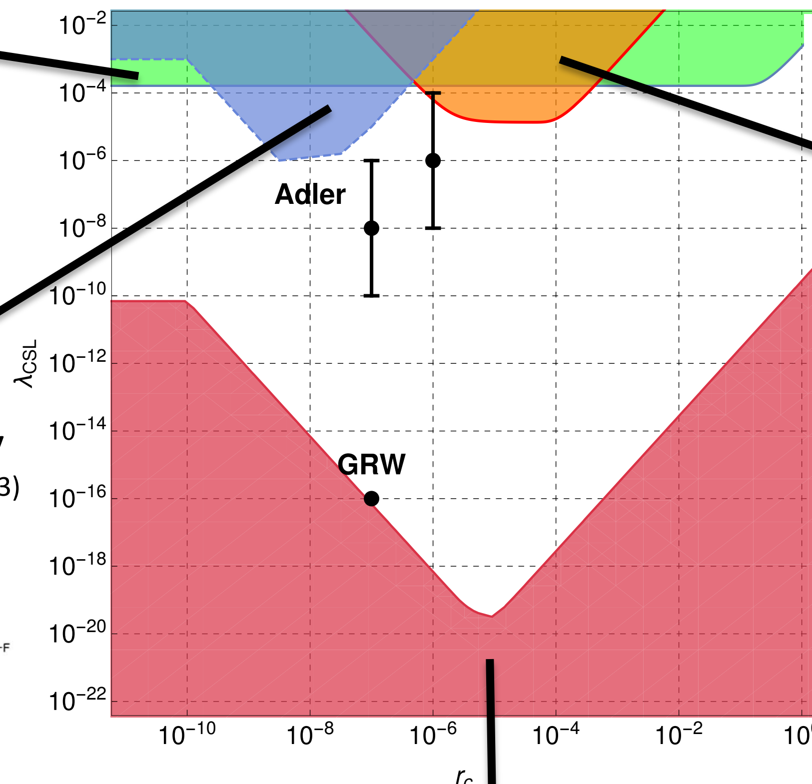
Prediction of collapse models
(no environmental noise)

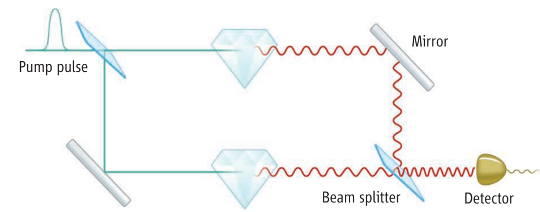
Interferometric Experiments

Atom Interferometry

T. Kovachy *et al.*, Nature 528, 530 (2015)

M = 87 amu
d = 0.54 m
T = 1 s

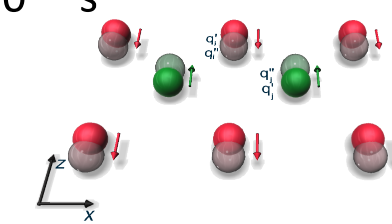




Entangling Diamonds

K. C. Lee *et al.*, Science. 334, 1253 (2011).

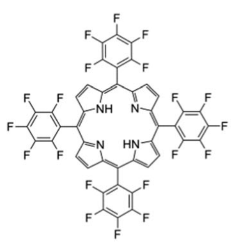
M = 10^{16} amu
d = 10^{-11} m
T = 10^{-12} s



Molecular Interferometry

S. Eibenberger *et al.* PCCP 15, 14696 (2013)

M = 10^{4} amu
d = 10^{-7} m
T = 10^{-3} s



TPPF20

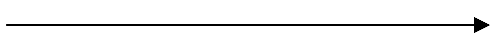
Lower bound: Collapse effective at the macroscopic level
Graphene disk: N = 10^{11} amu, d = 10^{-5} m, T = 10^{-2} s

Non interferometric tests

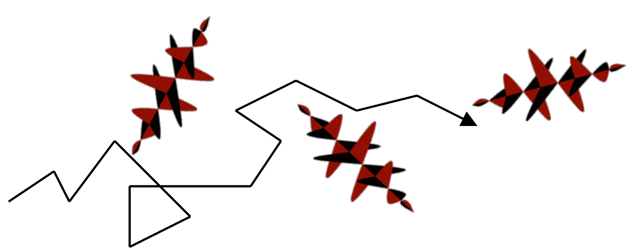
The collapse induces a **Brownian motion** on the system

Charged free particle

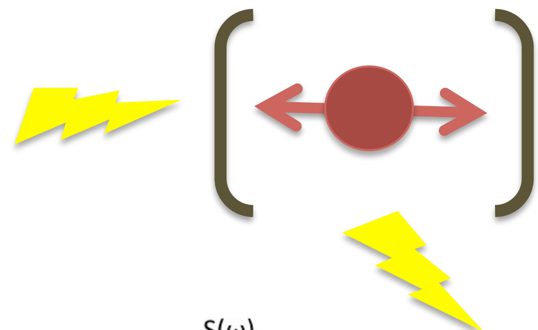
1. Quantum mechanics



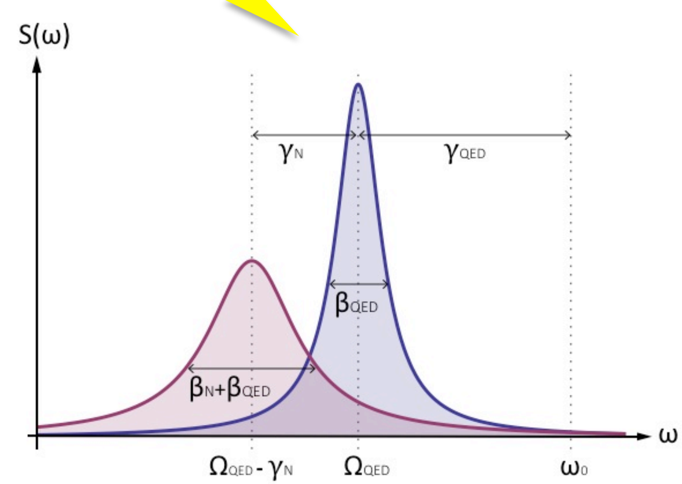
2. Collapse models



Spontaneous photon emission

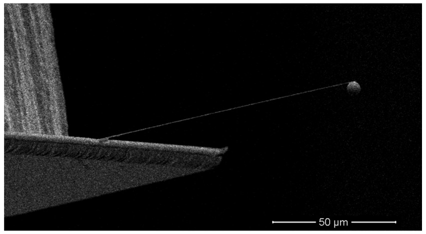


Nano-particle in a optical cavity



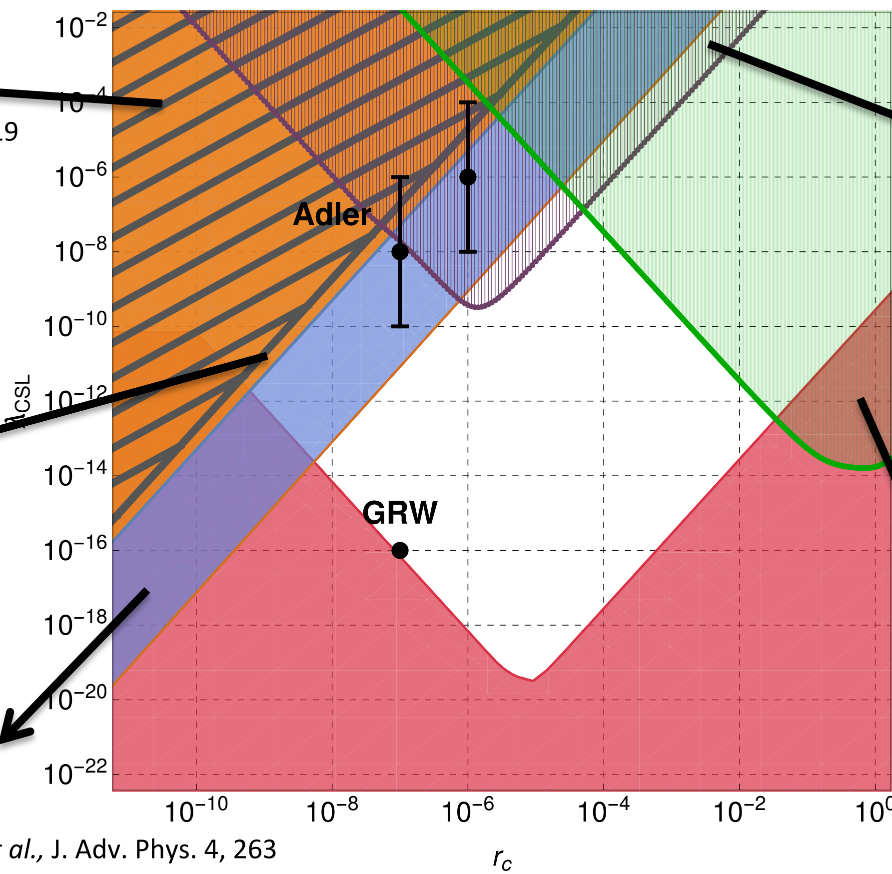
Extra shift and broadening

Non-Interferometric Experiments



Cold Atom Gas
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)

M = 87 amu
T = 30 s



Cantilever
A. Vinante *et al.,* Phys. Rev. Lett. 116, 090402 (2016)

M = 10^{14} amu
T = ∞

Cold Atom Gas
M. Bilardello *et al.,* in preparation

M = 87 amu
T = 1 s

X-Ray
C. Curceanu *et al.,* J. Adv. Phys. 4, 263 (2015).

M = 1 Kg
T = days / months

Auriga
M. Carlesso *et al.,* in preparation

M = 10^{30} amu
T = ∞

Earlier version: W. Feldmann, R. Tumulka, *J. Phys. A* 45, 065304 (2012)

Acknowledgments

The Group (www.qmts.it)

- Postdocs: M. Bahrami, S. Donadi, F. Fassioli, A. Grossardt
- Ph.D. students: G. Gasbarri, M. Toros, M. Bilardello, M. Carlesso, S. Bacchi, L. Curcuraci
- Graduate students: A. Rampichini

Collaborations with: S.L. Adler, M. Paternostro, A. Smirne, H. Ulbricht, A. Vinante, C. Curceanu.

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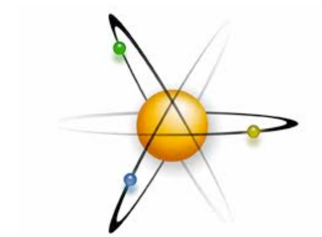
CSL Parameters



Microscopic world (few particles)

$$\lambda \sim 10^{-8\pm2}\mathrm{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (Adler - 2007)

Mesoscopic world: Latent image formation + perception in the eye (~ 10^4 - 10^5 particles)

S.L. Adler, JPA 40, 2935 (2007)

A. Bassi, D.A. Deckert & L. Ferialdi, EPL 92, 50006 (2010)

$$\lambda \sim 10^{-17}\mathrm{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (GRW - 1986)

Macroscopic world (> 10^{13} particles)

G.C. Ghirardi, A. Rimini and T. Weber, PRD 34, 470 (1986)

$$r_C = 1/\sqrt{\alpha} \sim 10^{-5}\mathrm{cm}$$

Increasing size of the system

Collapse models in space

REVIEW: A. Bassi and G.C. Ghirardi, *Phys. Rept.* 379, 257 (2003) **REVIEW**: A. Bassi, K. Lochan, S. Satin, T.P. Singh and H. Ulbricht, *Rev. Mod. Phys.* 85, 471 (2013)	**White noise models** All frequencies appear with the same weight	**Colored noise models** The noise can have an arbitrary spectrum
Infinite temperature models No dissipative effects	**GRW / CSL** G.C. Ghirardi, A. Rimini, T. Weber , *Phys. Rev. D* 34, 470 (1986) G.C. Ghirardi, P. Pearle, A. Rimini, *Phis. Rev. A* 42, 78 (1990) **QMUPL** L. Diosi, *Phys. Rev. A* 40, 1165 (1989) **DP** L. Diosi, *Phys. Rev. A* 40, 1165 (1989)	**Non-Markovian CSL** P. Pearle, in *Perspective in Quantum Reality* (1996) S.L. Adler & A. Bassi, *Journ. Phys. A* 41, 395308 (2008). arXiv: 0807.2846 **Non-Markovian QMUPL** A. Bassi & L. Ferialdi, *Phys. Rev. Lett.* 103, 050403 (2009)
Finite temperature models Dissipation and thermalization	**Dissipative QMUPL** A. Bassi, E. Ippoliti and B. Vacchini, *J. Phys. A* 38, 8017 (2005). **Dissipative GRW & CSL** A. Smirne, B. Vacchini & A. Bassi *Phys. Rev. A* 90, 062135 (2014) A. Smirne & A. Bassi *Nat. Sci. Rept.* 5, 12518 (2015)	**Non-Markovian & dissipative QMUPL** L. Ferialdi, A. Bassi *Phys. Rev. Lett.* 108, 170404 (2012)